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Rare Z Decays and New Physics[1]

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ABSTRACT

Although the signatures for rare Z decays are often spectacular, the predicted standard model rates are usually extremely small. In many cases, however, rare decays are very sensitive to new phenomena and may lead to an observable rate. In this talk, I select some interesting rare decays and discuss how new physics might be identified.

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Rare Z Decays and New Physics

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Abstract

Although the signatures for rare Z decays are often spectacular, the predicted standard model rates are usually extremely small. In many cases, however, rare decays are very sensitive to new phenomena and may lead to an observable rate. In this talk, I select some interesting rare decays and discuss how new physics might be identified.

1. Introduction

In the summer of 1989, experiments at LEP commenced and, in a few short months, the four experiments observed around 10^5 Z events between them. It is anticipated that each experiment will collect 10^6 events in 1990. With this data sample, it is possible to test the standard model both at the level of electroweak radiative corrections and by searching for rare decays of the Z. Although the signatures for rare decays are in many cases spectacular, the predicted branching rates are usually extremely small. On the other hand, rare decays are very sensitive to phenomena beyond the standard model, and attempts to isolate them may yield valuable information on new physics. Rather than catalogue the expectations for rare decays within the standard model [1], I will focus on a few decays, which, if observed, may lead to new physics.

2. Higgs Bosons

The most copious source of Higgs bosons in Z decay is the Bjorken process [2],

$$Z \to HZ^* \to Hf\bar{f}, \tag{1}$$

which, because of the large HZZ coupling, may have a branching ratio as large as 1% (see Fig. 1). For relatively light Higgs bosons, the rate for (1) summed over the fermions f is large enough that the few tens of thousands of events collected in 1989 at LEP are sufficient to set limits of $m_H > 25$ GeV [3] and $m_H > 24$ GeV [4] from OPAL and ALEPH respectively. Both of these limits make use of the $Z \to H\nu\bar{\nu}$ channel in addition to the smaller $Z \to H\ell^+\ell^-$ channel. Due to the Yukawa coupling with the fermions, the Higgs boson preferentially decays into the heaviest available fermion pair, which for $m_H \geq 10$ GeV means $H \to b\bar{b}$.

For light Higgs bosons, the $Z \to H\nu\bar{\nu}$ decay leads to a clean signal containing large amounts of missing energy accompanied by two jets. As m_H increases however, the missing energy decreases and the event appears more like a two jet event with some energy imbalance. Ordinary two jet events with missing energy generated by either the semileptonic

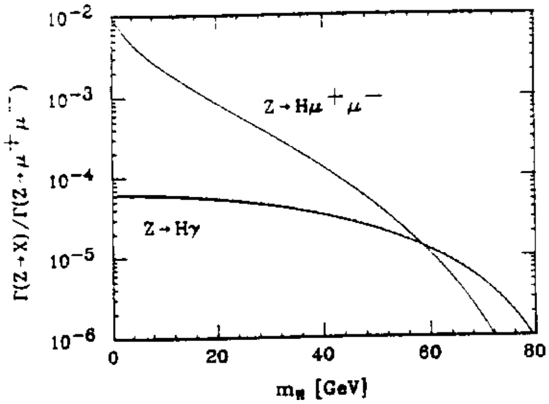

Figure 1: The decay rate, normalised to $\Gamma(Z \to \mu^+\mu^-)$ for (a) $Z \to H\mu^+\mu^-$, (b) $Z \to H\gamma$ for $m_t = 90$ (solid line) and 200 GeV (dotted line) as a function of the Higgs boson mass, m_H.

decay of a heavy quark, long lived neutrals or energy leakage then provide a significant background, leading to a reduced detection efficiency.

The $Z \to H\mu^+\mu^-$ decay channel is much cleaner and, in principle, the Higgs boson mass may be reconstructed from the muon four momenta,

$$m_H^2 = \hat{s} - 2\sqrt{\hat{s}}(E_{\mu^+} + E_{\mu^-}) + m_{\mu^+\mu^-}^2. \tag{2}$$

As m_H increases, the mass determination improves since the cancellations on the right hand side of (2) become smaller and less sensitive to the experimental resolution. Although the $Z \to \mu^+\mu^-$ branching rate is quite small, the event rate is significant (see Table 1).

m_H (GeV)	25	35	45	55	65
$Z \to H\mu\mu$	168	67	24	7.1	1.4
$Z \to H\gamma$	16.5 (16.7)	13.0 (13.3)	9.3 (9.6)	5.7 (5.9)	2.7 (2.9)

Table 1: Number of Higgs boson events in 10^7 Z events. We use $m_t = 90$ (200) GeV.

The signal consists of a pair of b quarks from the Higgs boson decay with $m_{b\bar{b}} \sim m_H$ and a muon pair from the decay of the virtual Z boson. Due to the effect of the Z propagator, $m_{\mu^+\mu^-}$ is as large as possible (see Fig. 2). The dominant background is the four fermion decay, $Z \to b\bar{b}\mu^+\mu^-$, or, since it is difficult to efficiently distinguish quark jets, $Z \to q\bar{q}\mu^+\mu^-$ [5]. However, as shown in Figs. 2 and 3, the background has a different structure in $m_{\mu^+\mu^-}$ and $m_{q\bar{q}}$ allowing a clean separation of signal and background for $m_H \lesssim 45$ GeV. Imposing an invariant mass cut on the muon pair, $m_{\mu^+\mu^-} > 20$ GeV, considerably reduces the background for heavy Higgs bosons while leaving the signal essentially untouched [5]. Provided that the experimental resolution on $m_{q\bar{q}}$ is O(few GeV), the discovery potential is only limited by the number of Z boson events obtained. With 10^6 (10^7) Z events, LEP can probe Higgs boson masses up to ~ 40 (60) GeV.

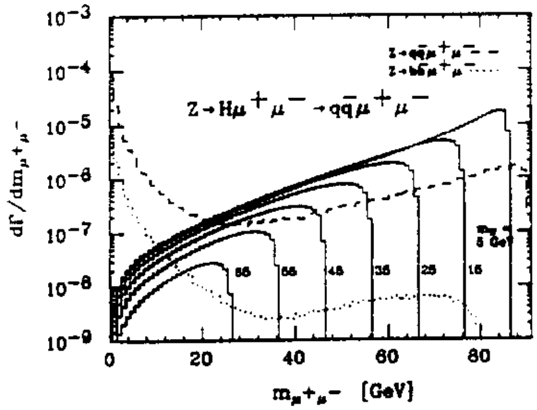

Figure 2: The invariant mass distribution of the muon pair, $d\Gamma/dm_{\mu^+\mu^-}$, produced in both $Z \to q\bar{q}\mu^+\mu^-$ decay and $Z \to H\mu^+\mu^- \to q\bar{q}\mu^+\mu^-$ decay for $m_H =$ 5, 15, 25, 35, 45, 55 and 65 GeV. The branching ratio for Higgs decay into heavy quarks, $H \to b\bar{b}$ and $H \to c\bar{c}$, has been folded into the signal, while the background is summed over all quark flavours. The contribution from $Z \to b\bar{b}\mu^+\mu^-$ is shown separately.

The Higgs particle may also be produced in association with a photon, $Z \to H\gamma$, which, because both the Z and H are neutral, occurs via top quark and W boson loops [6]. The branching fraction is therefore small (see Fig. 1), however, the phase space is larger than in the three body $Z \to H\mu^+\mu^-$ decay, and $Z \to H\gamma$ becomes important for $m_H \gtrsim 60$ GeV. Due to charge conjugation, the contribution from the top quark loop is proportional to the product of the electric charge and the small vector coupling with the Z. Therefore, the W loops dominate, leading to the very small top quark mass dependence shown in Table 1 and Fig. 1.

In principle, this decay is sensitive to the untested $WW\gamma$, WWZ and $WWZ\gamma$ vertices. Furthermore, because the Higgs boson couples to the mass of the particle in the loop, heavy particles do not decouple and the decay rate is sensitive to the existence of heavy particles that couple to both Z and γ. For example, in supersymmetric models, the scalar top quark and chargino loops contribute, and may change the decay rate appreciably [7]. Although, the $Z \to H\gamma$ rate is too small to effectively search for the Higgs, it would be an interesting

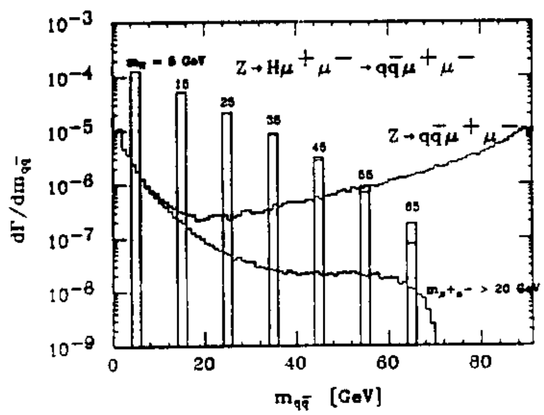

Figure 3: The invariant mass distribution of the quark pair, $d\Gamma/dm_{q\bar{q}}$ produced in both $Z \to q\bar{q}\mu^+\mu^-$ decay and $Z \to H\mu^+\mu^- \to q\bar{q}\mu^+\mu^-$ decay for $m_H =$ 5, 15, 25, 35, 45, 55 and 65 GeV. Both $H \to b\bar{b}$ and $H \to c\bar{c}$ decays are included in the signal, while the background is summed over all quark flavours. We also show the effect of making a cut on the invariant mass of the muon pair, $m_{\mu^+\mu^-} > 20$ GeV.

reaction to study once the Higgs boson has been found.

Finally, the Higgs boson may also be pair produced, $Z \to HHZ^* \to HHf\bar{f}$, [8] or produced with gluons, $Z \to Hgg$, [9]. Both of these decays are too rare to be seen at LEP.

3. W-Boson Production

The decay $Z \to Wf\bar{f}'$ was first proposed as a possible source of W-bosons [10], however, the branching rate for on-shell W production is rather small,

$$Br(Z \to W^{\pm}X) = 1.6\ 10^{-7}. \tag{3}$$

There are two reasons for this. Firstly, because of the relatively small $W - Z$ mass difference the available phase space is very small and secondly, there is a significant cancellation between diagrams containing the ZWW vertex and those which don't. Recently, Barger and Han [11] have investigated the contributions from off-shell W production in the $Z \to \ell^{\pm}\nu q\bar{q}'$ decay and find,

$$Br(Z \to \ell^{\pm}\nu q\bar{q}') = 1.5\ 10^{-7}, \tag{4}$$

three times larger than in the on-shell case.

The major backgrounds from $Z \to \tau^+\tau^-$, $b\bar{b}$ or $c\bar{c}$ followed by one leptonic and one hadronic decay are easily eliminated by isolation cuts on the charged lepton and missing energy vector and by an invariant mass cut on the invariant mass of the hadrons, $m_{hadron} > m_{\tau}$. Nevertheless, because of the gauge cancellation, the rate is too small to observe. On the other hand, if the ZWW vertex were to deviate from the standard model, the cancellations might be spoiled leading to an enhanced rate.

The most general Lorentz invariant effective Lagrangian for ZWW interactions may be described in terms of seven form-factors [12]. In models where mixing of the $SU(2)$ and $U(1)$ neutral gauge bosons occurs, electromagnetic gauge invariance eliminates three of these form-factors [13] while a fourth is heavily constrained by measurements of the neutron electric dipole moment [14]. The effective Lagrangian may then be written in terms of the

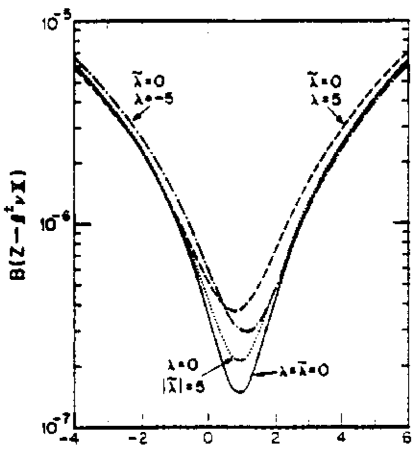

Figure 4: The $Z \to \ell^{\pm}\nu X$ branching fraction as a function of κ. The solid curve is for $\lambda = \tilde{\lambda} = 0$; the dotted curve is for $\lambda = 0$, $|\tilde{\lambda}| = 5$; the dashed curve is for $\lambda = 5$, $\tilde{\lambda} = 0$; the dot-dashed curve is for $\lambda = -5$, $\tilde{\lambda} = 0$. This figure is taken from ref. [11].

three remaining form-factors, κ, λ and the CP violating $\tilde{\lambda}$,

$$\frac{\mathcal{L}_{ZWW}}{g\cos\theta_W} = W^{\dagger}_{\mu\nu}W^{\mu}Z^{\nu} - W^{\dagger}_{\mu}Z_{\nu}W^{\mu\nu} + \kappa W^{\dagger}_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}Z^{\nu\lambda} + \frac{\tilde{\lambda}}{2M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}\epsilon^{\nu\lambda\alpha\beta}Z_{\alpha\beta}. \tag{5}$$

In the standard model, $\kappa = 1$, while $\lambda = \tilde{\lambda} = 0$. As shown in Fig. 4 [11], deviations from the standard model values can lead to a significant increase in the $Z \to \ell^{\pm}q\bar{q}'$ rate. After cuts to eliminate backgrounds, Barger and Han [11] find that with 5 10^7 Z events, one could test deviations of $\Delta\kappa = \pm 1$ at the 95% confidence level.

4. Lepton Flavour Violation

In the standard model lepton flavour is absolutely conserved. At LEP, it is possible to search for lepton flavour violating decays of the Z, the observation of which would then be a clear indication of physics beyond the standard model. Alternatively, the absence of such decays places potentially much more stringent bounds on lepton flavour violation than those from low energy data, and may restrict models which contain lepton flavour violation.

The most general lepton flavour violating (LFV) effective Lagrangian for interaction between leptons l_i and $\bar{l}_j$ is,

$$\mathcal{L}^{LFV}_{ij} = -\,i\,g_Z\,\bar{l}_i\,\gamma^{\mu}\left(a^{ij}_L\left(\frac{1-\gamma_5}{2}\right) + a^{ij}_R\left(\frac{1+\gamma_5}{2}\right)\right)\,Z_{\mu}\,l_j + \,g_Z\,\bar{l}_i\,\sigma^{\mu\nu}\,\frac{k_{\nu}}{M_Z}\left(b^{ij}_L\left(\frac{1-\gamma_5}{2}\right) + b^{ij}_R\left(\frac{1+\gamma_5}{2}\right)\right)\,Z_{\mu}\,l_j + \text{h.c.}, \tag{6}$$

where k_{ν} is the Z boson four momentum. Unlike the $b_L(b_R)$ terms, which must be generated via loop interactions, the $a_L(a_R)$ terms can arise either at tree level through mixing in models with extra exotic particles or at the one loop level, if the tree level couplings are flavour diagonal.

The branching ratio for lepton flavour violating Z decay into massless leptons is,

$$\frac{Br(Z \to l_i^+l_j^- + l_i^-l_j^+)}{Br(Z \to \mu^+\mu^-)} = \frac{2\,(a^{ij2}_L + a^{ij2}_R) + b^{ij2}_L + b^{ij2}_R}{c_L^2 + c_R^2}, \tag{7}$$

where $c_L = -\frac{1}{2} + \sin^2\theta_W$ and $c_R = \sin^2\theta_W$. Although the lepton violating couplings a^{ij}_L, a^{ij}_R, b^{ij}_L and b^{ij}_R are a priori unknown, some limits may be extracted from low energy data (see Table 2). We note that at low energy $k^2 \ll M_Z^2$, and therefore, low energy data is essentially insensitive to both b^{ij}_L and b^{ij}_R, and only a^{ij}_L and a^{ij}_R are constrained. Non zero values for b^{ij}_L and b^{ij}_R will increase the lepton flavour violating decay of the Z, and the observation of such decays at rates larger than the limits quoted below would indicate the presence of lepton flavour violating $\sigma^{\mu\nu}$ terms in the Lagrangian.

The event signature for the processes $Z \to e\tau$ or $\mu\tau$ is very distinctive. An energetic electron (muon) of beam energy recoils against a τ which then provides a well-defined

$l_i l_j$	Upper Limit	Process giving limit
$e\mu$	2.2×10^{-11}	$\mu \to eee$
$e\tau$	5.0×10^{-3}	$\tau \to e\rho$
$\mu\tau$	3.6×10^{-3}	$\tau \to \mu\mu\mu$

Table 2: Limits on $Br(Z \to l_i l_j)$ from low energy data.

signature of one or three charged prongs plus missing energy and momentum carried off by undetected neutrinos. Event selection and background suppression as well as the influence of the detector (resolution, inefficiencies, etc) have been discussed in ref. [15].

The limiting background is $Z \to \tau^+\tau^-$, where one $\tau^\pm \to e^\pm \nu_e \nu_\tau$ or $\tau^\pm \to \mu^\pm \nu_\mu \nu_\tau$, with electron (muon) energy close to the end-point of its spectrum. To suppress this background, one has to take advantage of the fact that the energy distribution of the electron (muon) produced in τ decays is a smooth linear distribution near the end-point, while the expected signal for the electron (muon) produced in the process $Z \to e\tau$ $(\mu\tau)$ would be (after convoluting with the detector resolution) roughly a Gaussian distribution with a radiative tail. For a detector of resolution $\sigma_E/E = 1\%$, the prediction [15] is,

$$\begin{aligned} Br(Z \to l^\pm \tau^\mp) &< 7 \times 10^{-5}\ (l = e, \mu) \text{ for } 10^6\ Z \text{ events}, \\ Br(Z \to l^\pm \tau^\mp) &< 7 \times 10^{-6}\ (l = e, \mu) \text{ for } 10^7\ Z \text{ events}, \end{aligned} \tag{8}$$

which improves the limits given in Table 2 by at least two orders of magnitude and begins to constrain exotic models.

5. Triple Photon Decays

Although the decay of an on-shell Z-boson into two photons is forbidden by Yang's theorem, the Z-boson may decay into three photons. In the standard model this is achieved through charged fermion or W boson loops.

Both triple gauge boson vertices ZWW and γWW contribute as do the quadruple gauge boson vertices $Z\gamma WW$ and $\gamma\gamma WW$. No estimate of the W loop contribution exists at present, however, due to the fact that $M_W > M_Z/2$, the W loops have already decoupled and their contribution is expected to be small.

As in the case of the $Z \to H\gamma$ decay, only the vector coupling contributes in the fermion loop and, ignoring the W-boson loop contributions, the three photon decay width is,

$$\Gamma(Z \to \gamma\gamma\gamma) = 0.7 \text{ eV}. \tag{9}$$

This is clearly unobservable at LEP.

On the other hand, composite models often generate a large $Z \to \gamma\gamma\gamma$ rate [16]. For example, if the Z boson is a bound state of constituents with electric charge Q, then [17],

$$Br(Z \to \gamma\gamma\gamma) = 2\ 10^{-4} < Q^3 >^2 . \tag{10}$$

Alternatively, residual four boson contact terms at a scale Λ can also lead to a sizeable branching ratio [16],

$$Br(Z \to \gamma\gamma\gamma) = 7\ 10^{-9} \left(\frac{m_Z}{\Lambda}\right)^8, \tag{11}$$

provided $\Lambda < m_Z$. Other possibilities also exist [18].

The limit of observability is determined by the pure QED process,

$$e^+e^- \to \gamma\gamma\gamma, \tag{12}$$

where, in general, two photons are energetic and approximately back-to-back while the third photon is relatively soft. This contrasts with the signal which is more 'Mercedes'-like with three well separated energetic photons. Nevertheless, current estimates [19] indicate that (12) provides an irreducible background corresponding to a $Z \to \gamma\gamma\gamma$ branching ratio of 10^{-5}. OPAL have placed a limit on the $Z \to \gamma\gamma\gamma$ branching ratio [20],

$$Br(Z \to \gamma\gamma\gamma) < 2.8\ 10^{-4}, \tag{13}$$

which still leaves a significant window for new physics.

Finally, there has been recent interest in the $Z \to \pi^0\gamma$ decay. Early estimates found the extremely small branching fraction of $\sim 10^{-11}$ [21] due mainly to the neutral current form-factor $\sim m_\pi^2/m_Z^2$ [22]. Jacob and Wu [23] have claimed that the axial anomaly prevents this form-factor dependence and find $Br(Z \to \pi^0\gamma) = 1.7\ 10^{-3}$. However, their arguments, based on soft pion results, are almost certainly wrong [24] and the $Z \to \pi^0\gamma$ decay is expected to be unobservable at LEP. Based on the absence of events of this nature in the 1989 data, OPAL and ALEPH place the limits,

$$\begin{aligned} Br(Z \to \pi^0\gamma) &< 3.9\ 10^{-4}, \quad [20] \\ Br(Z \to \pi^0\gamma) &< 4.9\ 10^{-4}. \quad [25] \end{aligned} \tag{14}$$

6. Summary

With a data sample of 10^6 Z boson events, experiments at LEP should be able to probe the Higgs sector up to $m_H \sim 40-45$ GeV, improve limits on lepton flavour violating decays by nearly two orders of magnitude and saturate the possibility of observing an anomalously large $Z \to \gamma\gamma\gamma$ rate. The observation of such events is a clear indication of new physics.

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